Renewable and Sustainable Energy Reviews 66 (2016) 852–860

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Aspects and issues of daylighting assessment: A review study

A. Galatioto*, M. Beccali

Dipartimento dell'Energia dell'Ingegneria dell'Informazione e dei Modelli Matematici, Università degli Studi di Palermo, Viale Delle Scienze Ed. 9, 90128 Palermo, Italy

ARTICLE INFO

Article history:
Received 12 August 2015
Received in revised form
5 February 2016
Accepted 12 August 2016
Available online 2 September 2016

Keywords:
Sustainable building design
Daylighting metrics
Glare
Lighting control strategies
Indoor visual comfort

ABSTRACT

Proper assessment of indoor daylighting conditions can significantly reduce energy consumption due to artificial lighting and can improve indoor visual comfort. This paper gives a critical review of the fundamental aspects of daylighting indices with the aim to provide a broad overview of methods and indices available to assess daylighting from varying points of view. Assessments cover distribution, availability over time and in specific climatic contexts, uniformity in the space, visual comfort issues and the relations between each of these aspects and a proper building and lighting design. A special focus on the assessment of indoor spatial and temporal uniformity is given. An analysis of the application of daylighting design by researchers and designers according to several area of interest is also presented.

Contents

1. Introduction

It is generally known that daylighting improves occupant comfort, health and work ability, especially in shared office spaces. In this framework, lighting design must ensure proper indoor lighting conditions that focus on the required lighting levels, available daylight and uniformity of illuminance values. In this way, an entire evaluation of the space is very important to ensure correct visual task performance due to daylight and, in the design phases, to fulfil the reduction of energy consumption from the use of artificial light.

Currently, both in lighting design and the scientific literature, the most commonly used parameters are focused on threshold or average values, which classify the entire space. The scientific community developed and validated many interesting assessment methods to fill a gap of the most accepted indices by providing a more detailed evaluation of visual ambient conditions. However, designers and researchers still have some difficulties and doubts in applying these methods because it is not clear which metrics should be implemented and which criteria should be recommended.

One of the most critical issues is the evaluation of illuminance level uniformity, which ensures safety and comfort both indoors and outdoors. In fact, the most commonly accepted performance indices rarely consider this fundamental parameter and rather focus on daylight availability and glare assessment.

To control outdoor lighting conditions, strategies often focus on

* Corresponding author.
E-mail addresses: alessandra.galatioto@dream.unipa.it (A. Galatioto), marco.beccali@dream.unipa.it (M. Beccali).

http://dx.doi.org/10.1016/j.rser.2016.08.018
1364-0321/

the safety and comfort of drivers or pedestrians (especially during the night) or on a particular building design. The EN Standards 13,201:2004 [1–5] clearly define criteria based on lighting levels and uniformity on road surfaces and classify road categories. Many studies have been published on this topic, e.g., Beccali et al. in 2015 [6] evaluated overall uniformity (UO), longitudinal uniformity (UL) and mean illuminance value on the road surface (E_m) in Comiso (Italy). Aubes et al. used a similar approach to assess the above-mentioned parameters on a refurbishment project of street lighting [7].

On the contrary, in indoor spaces that use both natural and artificial lighting, the lighting uniformity is more difficult to evaluate than in the outdoors because the cumulative indices often allow the identification of possible critical areas in the same space where the lighting conditions are very different from each other. This issue is one of the main issues in indoor lighting assessment. Better studies are needed. This study aims to provide a broad overview of methods and indices able to assess daylighting from several points of view, including distribution, availability over time and in specific climatic contexts, uniformity in the space, visual comfort issues and the relations between each of these aspects and a proper building and lighting design.

In the following sections, several performance indices have been analysed and reviewed to highlight their strengths and shortcomings, as well as to propose their use in sustainable design and/or redesign.

2. Assessment of average room conditions: *Daylight Factor and VH Ratio*

Availability is the main problem designers have in predicting daylight use. To achieve this, many simulations and calculations are often necessary. Currently, all scientific methods are developed starting from the first daylighting coefficients proposed by Tregenza in 1980 [8]. According to Tregenza, the daylight coefficient for a given point and portion of sky determines the strong relation between the illuminance value on a point and the luminance of the portion of sky according to the following Eq. (1):

$$\Delta E_{l,\vartheta,\phi} = D_{l,\vartheta,\phi} \cdot L_{l,\vartheta,\phi} \cdot \Delta\omega_{\vartheta,\phi} \tag{1}$$

where φ azimuth; ϑ altitude; $DE_{i,\vartheta,\varphi}$, are the contribution of the total direct and indirect illuminance at a given point i due to the sky [lux]; $D_{i,\vartheta,\varphi}$ is the daylight coefficient for reference [lux]; $L_{\vartheta,\varphi}$ is the luminance of the sky element [cd/m^2]; $D\omega_{\vartheta,\varphi}$ is the solid angle of the sky element [sr].

The Daylight Factor (DF) is equal to the ratio of daylight illuminance at a point within a space to the exterior illuminance under an unobstructed overcast sky. According to the well-known ratio (2)

$$DF = \frac{E_{in}}{E_{out}} \tag{2}$$

The Daylight Factor depends on several characteristics of a space: the sun orientation, the shape of the space, the surface reflectivity, and the daylight penetration into the adjoining spaces.

Furthermore, the DF depends on the window and room orientation and any surrounding obstruction and the optical phenomena such as transmission, reflection and light scattering that occur throughout the windows [9]. In building design, estimation of the Daylight Factor is used to define sufficient internal daylighting for the occupants, as well as comfortable performance of their visual tasks [10,11].

In the past, many researchers studied DF extensively at ground level while considering several undeveloped aspects. For instance, the Chartered Institution of Building Services Engineers (CIBSE) developed a very interesting Daylight Factor Model (DFM) [12,13] for a building at the ground surface in 1999 that was validated experimentally by Chel et al. in 2009 [14] without considering the time of day or height of the workspace. In 2015, Sudan et al. developed a DFM for daylight through windows that was experimentally validated for east-oriented wall windows under clear sky conditions [15]. This DFM has been performed while considering inclination, position and orientation (South, North, East or West) of the window with reference to the sun. The results indicate that the proposed DFM can be used for any building by changing the fundamental parameters.

Today, lighting simulation software has a high accuracy in calculating Daylight Factors. An example of this calculation has been performed by Ghisi et al. [16]. The authors developed a computation method via VisualDOE [17] to correlate the Daylight Factor prediction and potential related energy savings. This study has been conducted using ten different dimensions and room ratios in the UK. The authors found that smaller rooms have better energy savings due to artificial lighting reduction, and the ideal window area is higher in low thermal load orientations.

Acosta et al. reported similar findings [18] in their use of Daylight Visualizer 2.6 [19] to evaluate several indoor spaces and affirmed that the DF is directly proportional to the glass surface except for the area near the window. They also demonstrated that square windows cause somewhat higher DF values than those obtained with horizontal windows—values noticeably higher than those measured with vertical windows. In addition, the correlation between energy savings and predicted daylighting is the most important tool for designers and architects.

With regards to the correlation between energy savings and visual performance, Linhart and Scatterzini demonstrated via experiments in an office space that the conventionally adopted value of 5 W/m^2 for internal lighting loads can guarantee users' visual comfort [20].

However, it is well-known that the DF is only based on the Overcast Sky CIE model that is symmetric across all orientations. The authors show that different sky conditions or models, as well as window orientations, cannot be evaluated using this index. Furthermore, it cannot be used to indicate illumination levels due to a combination of natural and artificial light sources. It cannot provide information about glare from natural light or assess indoor lighting.

In 1993, Love [21] showed that the most important limitation of DF is its poor suitability for direct sunlight in indoor or outdoor spaces, despite the seeming simplicity of indoor and outdoor illumination. There are many issues due to the variability in sky conditions that affect its reliability. In this way, Love and Navvab [22] proposed the *VH Ratio* (Vertical to Horizontal illuminance) to overcome some DF limits. The *VH* is the ratio between vertical illuminance (E_V) and horizontal illuminance values (E_H). It is calculated according to Eq. (3) and is better and more helpful than the DF.

$$VH = \frac{E_v}{E_H} \tag{3}$$

The VH ratio is a function of the light decrease on a vertical plane, while the DF is the function of light decrease on a horizontal plane. According to human perception researchers, the lighting of vertical surfaces is more important than the lighting of the work plane, especially in working spaces [23]. Hence, the variability of the DF (in terms of the range of indicator values under clear, overcast, and partly cloudy sky conditions) has been assessed. According to Love and Navvab, this variability results in about one-sixth under clear and partly cloudy skies and one-third or less under overcast skies.

Furthermore, the authors declared that the VH ratio was superior to DF with respect to the assessment of illumination quality. In fact, it also provides useful information about direct sunlight. Furthermore, it can be used under any sky conditions, and it provides information about light directionality. It is affected by the effects of architectural features (such as the light shelf or tents). Mardaljevic et al. highlighted additional limitations of the Daylight Factor [24] in 2009. In the following sections, we discuss other comparisons between DF and existing performance indices.

2.1. Assessment over time: daylight autonomy, continuous daylight autonomy and useful daylight illuminance

In 1989, the Daylight Autonomy (DA) parameter was proposed by the "Association Suisse des Electriciens" and developed by Reinhart from 2001 to 2004 [25]. It was the first dynamic approach for daylighting indoor evaluation and focused on the temporal occurrence of natural light. In fact, DA represents the percentage of hours during the year when the illuminance values overcome a predefined threshold [26]. Furthermore, Reinhart and Weissman tested the early stage of the Lighting Measurement protocol for Spatial Daylight Autonomy at Corbusier's Carpenter Center in Cambridge [27,28]. However, the DA definition does not provide a fixed threshold value. Olbina and Beliveau proposed a value threshold in 2009 [29]. They suggested that the threshold (E_{lim}) be set to 500 lx according to Eq. (4):

$$DA = \frac{\sum_i \left(wf_i t_i\right)}{\sum_i t_i} \in \left[0,\ 1\right] \qquad wf_i = \begin{Bmatrix} 1 & \text{if} & E_{Daylight} \ge E_{lim} \\ 0 & \text{if} & E_{Daylight} \le E_{lim} \end{Bmatrix} \tag{4}$$

Here, t_i is each occupied hour in a year, $E_{Daylight}$ is the horizontal illuminance at a given point and wf_i is a weighting factor. According to daylight metric methods, several variables must be considered, including the time frame, spatial consideration, target illuminance and location and climate. The time frame is referred to as occupied spaces and daylight hours. Spatial consideration determines a specific point in a daylit space and generally represents a worst-case or minimal annual illuminance level. Obviously, calculation at a specific point is not representative of the overall space when the daylight uniformity analysis is performed. In this way, as suggested by Rogers, daylight uniformity measurements and any worst-case points are included in the overall calculation.

Target illuminance defines the illuminance threshold to be used for calculating the contribution of daylight. Location and climate consider latitude and longitude and weather data to use in the annual simulation, respectively [30].

However, DA does not provide relevance to lighting values below the established lighting threshold nor to the ones over it. Rogers developed a new parameter called the continuous Daylight Autonomy (cDA) that further defines thresholds to specific visual tasks (e.g., below 500 lx) [31]. The cDA index is a modification of the DA by linear assignment of partial credit to values below the specified illumination level threshold. With respect to the DA definitions, cDA aims to attribute time step credits when the illuminance values lies below the minimum. As explained by Reinhart et al., this approach permits one to consider a threshold that is more adaptable to a subject's preference (e.g., lighting requirement of a room: 600 lx; provided daylight level: 500 lx; attributed partial credit at the time step: 500/600 = 0.8).

According to Rogers' tests, the yearly distribution of "daylight saturation" is determined and provides a measure of the daylight uniformity for a given space. In fact, Rogers found that rooms with good uniform daylight saturation achieve adequate DA for at least 60% of the workplace. Moreover, several authors defined new dynamic performance indices according to Climate-based daylight modelling (CBDM) [32]. CBDM predicts various radiant or luminous values using sun and sky conditions that are derived from standard meteorological datasets to evaluate indoor daylight availability for dynamic approach assessment.

Useful daylight illuminance (UDI) was developed by Nabil and Mardaljevic and addresses a new paradigm for lighting assessment via the ranges of illuminance values that guarantee indoor comfort according to the visual task. The UDI is an interpretation tool for daylight levels datasets. It is based on actual weather data during a specific period of the year [33]. The UDI parameter is split into three thresholds: UDI fell-short (UDI-s < 100 lx), UDI achieved (UDI-a from 100 lx to 2000 lx) and UDI exceed (UDI-e > 2000 lx). It is a very interesting index for preliminary daylighting mapping. The second range of lux values results in very large and accurate daylighting levels as a function of a specific visual task.

The DA and UDI consider the fraction of operating hours (occurrences) throughout the year when the target value (minimum value in the case of DA and a range in the case of UDI) is fulfilled. For 300 lx, the DA is very similar to UDI-a. The main difference is that the UDI scheme includes the number of times it exceeds the higher illuminance limit (in this case 3000 lx). Thus, the annual occurrence of UDI-a will generally be less than that for DA at 300 lx.

Nabil and Mardaljevic compared the UDI, DA and DF indices. The authors affirmed that UDI is more suitable for simple evaluation of the effects of architecture and lighting design options. The UDI and DA parameters have been calculated through the CIBSE Test Reference Year TRY London Latitude dataset; the DF has been assessed with CIE overcast sky conditions [34]. Several issues related to DA and UDI metrics have been analysed by Saraiji et al. They proposed the Normalized Daylight Performance Index (NDI). The NDI does not replace other daylight performance indices, but it does provide a useful tool for designers who need to evaluate the increase or decrease of performance variables [35].

A wide family of indices are based on the assessment of visual tasks. In 2008, Cetegen and Veitch affirmed that into a room both the average luminance and luminance variation influence the occupant's judgements [36]. Tiller and Veitch discovered that the luminance distribution across an occupant's field-of-view, as well as the strength of its variation, are preference factors [37]. In this way, Rockcastle and Andersen analysed luminance and illuminance yearly variation. They compared the above-mentioned dynamic indices and correlated them to the perceived lighting space. As highlighted by the authors, both the DF and dynamic indices are derived from four fundamental photometric parameters: luminous flux, intensity, illuminance and luminance. Therefore, the space is described in only two dimensions [38]. The proposed annual luminance variability (ALV) index is defined by Eq. (5):

$$ALV = \frac{\sum_{h=1}^{nh} \sum_{d=1}^{nd} \overline{\Delta PLh,\ d}}{\Delta P\max_{h,d}} * 100 \tag{5}$$

where $\Delta P_{h,d}$ is the luminance variability calculated according to Eq. (6):

$$\overline{\Delta P_{h,d}} = \frac{1}{4}\Big(\left|P_{h,d} - P_{h+1,d}\right| + \left|P_{h,d} - P_{h-1,d}\right| + \left|P_{h,d} - P_{h,d+1}\right| + \left|P_{h,d} - P_{h,d-1}\right|\Big) \tag{6}$$

for all $P = 1 \rightarrow n_h$ (number of hourly instances) and $j = 1 \rightarrow n_d$ (number of daily instance).

The authors compared the DF, DA, UDI, DGP and ALV metrics. ALV provides more information about the lighting quality of the indoor space and the dynamic perceptual time and spatial-based effects on the occupants and describes dynamic visual discomfort conditions.

To quantify the visual effects related to dynamic performance indices, a different approach has been adopted by Sicurella et al. These authors analysed the visual impact of DA and UDI in terms of discomfort and proposed a new indicator called the intensity of visual discomfort (IVD) [39]. The IVD is the time difference between the spatial average of the current daylight illuminance and the upper limit of visual comfort (set at 750 lx) or the lower limit (E_{under}; set here to 150 lx). The IVD is defined according to Eqs. (7) and (8):

$$IVD_{over} = \int_P \Delta E_{over}(\tau)\cdot d\tau \quad where \ \ \Delta E_{over}(\tau) = \begin{Bmatrix} E(\tau) - E_{over} & if \ E(\tau) \geq E_{over} \\ 0 & if \ E(\tau) < E_{over} \end{Bmatrix} \tag{7}$$

$$IVD_{undr} = \int_P \Delta E_{under}(\tau)\cdot d\tau \quad where \ \ \Delta E_{under}(\tau) = \begin{Bmatrix} E_{under} - E(\tau) & if \ E(\tau) \leq E_{under} \\ 0 & if \ E(\tau) > E_{under} \end{Bmatrix} \tag{8}$$

3. The issue of reliability of weather data

The DF, DA and UDI indicators allow easy predictions of daylighting environmental performance, but it must be considered that they are calculated via dynamic simulations. These consist of different computation steps that start with external luminous conditions. These software can convert global and diffuse irradiance values and are contained in weather data files to generate a sky luminance distribution via the sky model. Different weather data are available, and Bellia et al. compared two different research steps [40,41]. The Meteonorm [42], test reference year (TRY) and International Weather for Energy Calculations (IWEC) were used as outcome metrics. Obviously, these data are based on different historical sets of annual weather measurements (generally composed of 20 years). This is based on a typical year definition via a statistical assessment. This study was performed by comparing the same space at different latitudes with the above-mentioned weather data.

The authors demonstrated that the use of IWEC, Meteonorm and Satel-Light weather files for dynamic daylight simulations leads to similar outcomes. This study highlighted that the evaluation of dynamic daylight indicators (DA, cDA and UDI) is directly linked to proper lighting design and lighting energy consumption.

4. Excess daylighting: indoor glare evaluation indices

As mentioned above, optimization of daylight use is one of the most important qualities of the space and improves energy savings and visual comfort. Although the previous indices can predict daylight availability, it is always suggested that one should assess the main issues of possible discomfort such as glare. The visual comfort in daylit spaces can be assessed by proper assessment of occupant judgements through an evaluation test [43–45]. It can also be evaluated by the occurrence of glare and its effects on the occupants.

According to the IESNA handbook, glare is defined as “the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort, or loss in visual performance and visibility” [46]. Furthermore, in the CIBSE Lighting Guide LG7, glare is defined as a ”condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or to extreme contrasts” [47].

As is well-known, there are two types of glare: disability glare and discomfort glare. In the first one, light reaches the eye and causes a reduction in visibility and visual performance. The second one leads to users' discomfort. It often has less immediately noticeable effects such as headaches or posture-related aches after work [48]. Starting from the modified Cornell formula by Hopkinson [49–51], Nazzal proposed the Daylight Glare Index [52] in Eqs. (9) and (10):

$$DGI = 10 \log \sum_{i=1}^{n} G_i \tag{9}$$

$$G_i = 0.478\left(\frac{E_s^{1.6}\cdot\Omega_i^{0.8}}{L_b(0.07\omega^{0.5}\cdot L_w)}\right) \tag{10}$$

where L_s is the luminance of each part of the source [cd/m^2]; L_b is the average luminance of the surfaces in the environment within the field of view [cd/m^2]; L_w is the weighted average luminance of the window in a function of the relative areas of sky that is obstructed and ground [cd/m^2]; ω is the solid angle of the window [sr]; and Ω is the solid angle of the source modified as a function of the line of sight [sr].

Another useful index of discomfort is the daylight glare probability (DGP). It was derived by Guth from experimental comparisons related to an office space. It considers the involvement of subjects [53–55]. The basic Eq. (11) derived by Wienold and Christoffersen in 2006 [56] for DGP is

$$DGP = c_1 E_v + c_2 \log\left(1 + \sum_i \frac{L_{s,i}^2\ \omega_{s,i}}{E_v^{c_4} P_i^2}\right) + c_3 \tag{11}$$

where E_v is the vertical illuminance at the eye [lux]; L_s is the luminance of the source [cd/m^2]; ω_s is the solid angle of the source [sr]; and P is the Guth position index [–].

According to Wienold's study, DGP provides a comprehensive yearly analysis of glare phenomena. The simplified Daylight Glare Probability DGPs [57] was defined by Eq. (12).

$$DGP_s = 6.22\cdot 10^{-5}\cdot E_v + 0.184 \tag{12}$$

DGP is the only index based on vertical eye illuminance and hence it is strongly linked to the occupant's lighting perception during that time. It is used to compare different design solutions, as well as control strategies. It can be easily calculated via DAYSIM software [58]. However, the equation does not consider the contribution of individual glare sources. It can be applied on spaces without direct sun or specular reflection that reaches the subject's eye. Furthermore, Konstantzos et al. have demonstrated that DGPs are not accurate when the sun is within the field-of-view [59,60].

To identify criteria of glare metrics that were also suitable for yearly simulations, Wienold (2009) proposed a set of ‘comfort classes’ (A, B and C) based on the method of thermal comfort analysis. These classes were based on the time of space occupation. The current recommendation is that 95% of the DGPs occurrences should be below a threshold value to be assigned to a specific class. In this way, the space is classified as: A (best class) when at least 95% of the office-time glare is ‘imperceptible’; B (good class) when at least 95% of the office-time glare is ‘perceptible’ and C (reasonable class) when at least 95% of the office-time glare is ‘disturbing’. These two metrics give information about the spatial and temporal quality of daylit spaces [61]. Guth also developed an index called the visual comfort probability (VCP) that assesses the subject's response to glare conditions. The VCP is defined as the percentage of people who will find a certain space comfortable with regard to visual glare [62,63]. Furthermore, the well-known unified glare rating (UGR) can also describe lighting space with a uniform lighting source [64]. According to Eq. (13) UGR is

$$UGR = 8\,\log\left[\frac{0.25}{L_b}\sum_{i=1}^{n}\frac{L_i^2\omega_i}{P_i^2}\right] \tag{13}$$

where L_b is the background luminance [cd/m^2]; L_i is the luminance of luminaire i [cd/m^2]; ω_s is the solid angle of the source [sr]; and P is the Guth position index [–].

In the UGR definition, each luminaire is a uniform light source characterized by one luminance level, one position index and one solid angle in the subject's field-of-view. The equation is applicable for sources having solid angles between 0.1 and 0.0003 sr. As affirmed by Scheir et al., the Guth position index is specified only for the upper visual field, and it is obtained by interpolating the standardized values.

Scheir et al. calculated UGR maps with different luminance distributions and applied uniform and non-uniform luminance light sources [65]. The authors considered each luminance source and combined them as a unique large source. In fact, considering a uniform light source, the UGR is independent from the luminance map distribution, but is dependent on the individual source configuration. The authors found that for uniform light sources, the UGR is a very useful tool to appreciate the luminance distribution. For non-uniform sources, the UGR results in a range depending on the number of meshes. In conclusion, the UGR cannot define the distribution quality of luminance. Furthermore, in 2001, Nazzal found that the VCP is intrinsically not applicable for daylight assessment [52].

However, in 2013, Suk et al. highlighted that the existing methods do not accurately describe glare issues when extremely bright glare sources are involved [66]. The authors compared many indices (DGP, DGI, UGR and VCP) and also proposed three different luminance ranges to assess an absolute glare factor, a relative glare factor and a no-glare condition. In 2012, Mardaljevic et al. analysed the correlation between UDI and DGPs to assess the occurrence of glare and UDI prediction [67]. As is well-known, the UDI definition simply accounts for the annual occurrence of illuminance values across the work plane that are within a range considered “useful” by the occupants. Furthermore, most subjects consider comfortable conditions to occur when there is a lighting level of approximately 100 lx. They tend to tolerate much lower illuminance levels of daylight than artificial light [68]. Authors highlighted that a computational analysis of DGPs showed that the contrast terms need more detailed analysis, especially under low illuminance conditions. The study demonstrates a robust correlation between UDI-a, UDI-e and DGPs.

Further studies to enhance this method are necessary. In fact, these analysed indices can assess a range of illuminance values and related glare probabilities. They do not provide any information about spatial and temporal distribution of the values. In the following section, several methods about spatial and temporal data assessment are reported.

5. Assessment of temporal and spatial uniformity

The uniformity of illuminance values describes the quality of lighting space where the subject performs visual a task. However, most recommendations are based on a balance between the illuminance on the working plane and on the adjoining zones [69]. As is well-known, the illuminance uniformity is expressed as a ratio of the minimum illuminance to the average illuminance on a surface according to Eq. (14):

$$UR = \frac{E_{\min}}{E_{avg}} \tag{14}$$

The CIBSE recommends that the working plane illuminance should have a minimum uniformity rate of 0.8 [70], and the IES guidelines recommend to minimize the illuminance level variations throughout a space and on the working planes [71]. Hence, higher illuminance uniformity implies better occupant visual comfort [72]. Furthermore, this approach is also used in the case of very large spaces. Moreover, as demonstrate by Andersen in 2008 through the LightSolve approach [73,74] and confirmed by Carlucci in 2015 [75], the uniformity of light is the most useful parameter that can describe the quality of the space via a single value. However, it can also represent similar and different lighting zones. In other words, the preliminary design phase can be a false tool to predict the visual conditions of the subjects.

Carlucci et al. proposed a review of indices for assessing visual comfort. The authors offered a whole synoptic analysis of the visual comfort metrics. They classified indices in families via spatial and temporal discretization. In fact, as abovementioned, the existing metrics are based on time-series and cumulative indices. Furthermore, they consider the visual comfort assessment to adopt “short-term” and “long-term” evaluation according to the thermal comfort analogy. In this way, several daylighting performance indices and studies have been critically analysed.

Van Den Wymelenberg et al. also critically analysed the common lighting metric with correlation to human responses [76]. The authors conducted an experimental setup with 93 participants from June to December 2011 (from 8:30 a.m. to 4:00 p.m.) at the University of Idaho in Boise. This period was selected because the sunny days represent most study hours. The results highlighted the limitations of the existing illuminance and luminance-based lighting quality guidelines [77]. Particularly, in relation to the occupant's visual comfort, it is restricted to relatively small areas that comprise less than 5% of the field-of-view, as demonstrated by Sutter et al. in a pilot study on shading system use [78].

Moreover, Chou et al. highlighted the importance of uniformity for classrooms in Taiwan [79]. Ho et al. [80] demonstrated that the proper use of sun-shadings is a suitable tool to improve the illuminance uniformity ratio, as well as the occupant's visual comfort. In this way, the illuminance uniformity ratio is one of the most important parameters in lighting evaluation. However, the uniformity ratio is also a value that cannot be applied to a whole indoor space and is characterized by different “lighting zones”. In this regard, many statistical methods have been developed. Mathieu [81] proposed the statistical uniformity (SU) according to Eq. (15):

$$SU = \frac{E_m + E_{sd}}{E_m - E_{sd}} \tag{15}$$

Here, E_m is the average illuminance value, and E_{sd} is the standard deviation of the values sample. Furthermore, Armstrong [82] proposed the coefficient of variance (CV) according to equation (16):

$$CV = \frac{E_{sd}}{E_m} \tag{16}$$

Despite the above-mentioned indices that analyse the uniformity issue, Mahdavi and Pal proposed a new analysis approach via an entropy-based method [83]. In particular, they analysed the spatial distribution of the values in some spaces and compared several uniformity indices called the “first generation indices” and “second generation indices”. In addition, they proposed a new index Entropy-based Distribution Index (EDI) based on the signalling concept (Eqs. (17)–(19)).

$$EDI = \frac{100}{n}\sum_{i=1}^{n}\left(P_{i,g}\cdot P_{i,l}\right)^{0.5} \tag{17}$$

$$P_{i,g} = 1 - \frac{|E_i - E_{m,g}|}{|E_{m,g} - E_{sd}|} \tag{18}$$

$$P_{i,l} = 1 - \frac{|E_{m,l,i} - E_{m,g}|}{|E_{m,g} - E_{sd}|} \tag{19}$$

where $P_{i,g}$ is the global probability; $P_{i,l}$ is the local probability; E_i is the illuminance levels at a point; $E_{m,g}$ is the average illuminance of the whole space; E_{sd} is the standard deviation of the illuminance values of the whole space; and $E_{m,l,\ i}$ is the local average illuminance of the immediate adjoining of the grid point i.

In other words, EDI critically characterizes certain ranges of values on a grid to define the lighting conditions and improve visual performance of the occupants. Mahdavi and Pal demonstrated the potentiality of entropy-based measurements of the light distribution uniformity. The EDI solves the issues related to value distribution. Information has been provided about their time distribution. In this way, Galatioto et al. [84] studied the time distribution via an information theory metric approach [85,86] to better estimate the illuminance data series deriving from measurements or simulations. This approach is based on the Shannon–Wiever equation (20):

$$H = \sum_{i=1}^{n} p_i \ln p_i^n \tag{20}$$

where H is the entropy of the series, p_i is the probability of the i-th signal, and ln is the natural logarithm.

According to the Shannon–Wiever study [87], the entropic-probabilistic analysis has been applied to a set of illuminance data in a sample space and a $H/H_{max\text{-}T}$ ratio was proposed.

$H_{max\text{-}T}$ is the maximum entropy that the series would have if all the values had the same probability of occurrence. The authors also compared DF, DA and UDI indices. It must be noted that a good correlation between DF and $H/H_{max\text{-}T}$ ratio has been found. In particular, authors observed that at an average DF of $\sim$12%, the $H_{max\text{-}T}$ value occurs. The minimum $H_{max\text{-}T}$ value occurs with an average DF of $\sim$20%. In this way, the authors suggested that high DF and DA values can maximize discomfort for the occupants due to non-uniformity. In both cases of EDI and $H/H_{max\text{-}T}$ indices, the researchers proposed methods that can be used in any space. Neither index is a replacement of the existing ones but a complementary means to represent information.

The above-mentioned uniformity of values strongly influences the indoor visual comfort. Greenup and colleagues used this to show a correlation between visual and thermal discomfort [88]. First of all, the authors highlighted that lighting/daylighting simulations are affected by use of radiosity or raytracing methods that do not accurately consider surface lighting redirection [89,90]. The authors developed a model based on a combination of the above-mentioned methods that was implemented for each sky condition.

6. Sustainable building design: performance indices for choice and energy savings

Many issues occur in sustainable building design dealing with a proper balance between natural lighting, solar radiation control, visual comfort and energy consumption related to artificial lighting, heating and cooling demand and thermal comfort. This is today a capital issue for architects and designers. Certainly, an appropriate assessment of daylighting "quantity and quality" is a starting point for windows dimensioning, positioning, choice of glasses, as well as for dimensioning shading devices.

Glazing areas have a very important role, not only in guaranteeing indoor visual comfort conditions but also in achieving a sustainable environment and reducing risks in particular rooms, such as museums [91–93]. However, this extra light can also lead to extra heat, which is problematic in the summer season as it can in turn increase energy use. Daylight control strategies consider both passive and active shading device systems (e.g., light shelves or venetian blinds) and active control of artificial lighting dimming systems. Furthermore, proper light sources installation may maximize energy savings and users' visual comfort. Reinhart and Walkenorst estimated how the yearly indoor daylighting availability measurements are representative of DAYSIM software [94]. Several configurations in office spaces equipped with double glazed venetian blinds have been performed. During building design or refurbishment, it is a best practice to limit and control the solar radiation penetration.

In this way, many studies have focused on the prediction and control of the glare phenomena that redefines the subject's tolerance value threshold [95]. Fewer studies are concerned with luminance non-uniformity issues [96,97]; most studies focus on venetian blinds. Alzoubi and Al-Zoubi analysed many variables affecting the illuminance levels in spaces. They studied an office room that consisted of simple horizontal and vertical louvers with different tilts [98]. They considered thermal and lighting materials proprieties. They correlated DF decreases and distance from windows and found a good effect on the working plane. In particular, the shading device applications involved illuminance distribution increases, illuminance values decreases, and a reduction in the thermal loads. The same shading typologies strategy was studied by Sherif et al. under clear sky conditions. In this case, the authors studied the effects of the changing solar screen angle rotation on indoor glare phenomena and yearly daylight availability [99].

Chaiwiwatworakul et al. studied the daylighting effects of an automated venetian blind system integrated with a room dimming control system. The experiment was conducted for a whole year, and the authors evaluated the effect of the system on vertical and horizontal illuminance values and DGI. The authors demonstrated that energy savings of up to 80% can be achieved, and indoor visual conditions are significantly improved [100].

Hu and Olbina (2011) developed an Illuminance-based Slat Angle Selection (ISAS) model. This model predicts the optimum slat angles of split blinds to achieve the designed indoor illuminance that overcomes the manual-control shading limitations. The ISAS model has been built via a series of multi-layer feed-forward artificial neural networks (ANNs). The data were derived from EnergyPlus software that is based on the radiosity method [101,102]. In addition, the authors compared the UDI-predicted results derived from ANNs and current UDI at given points and found slat angles for different sections at a particular point in time.

Furthermore, UDI has been utilized by Li et al. to evaluate the effect of building integrated solar technologies (BIST) in horizontal and vertical louvers on different orientation windows [103]. Authors have analysed different BIST configurations and have chosen the better one by balancing the results in terms of energy saving and indoor visual outcomes.

Chan and Tzempelikos developed new venetian blind control strategies that considered daylight prediction, lighting energy use and indoor visual comfort [104–106]. The authors calculated solar transmission through the window-blind system, indoor

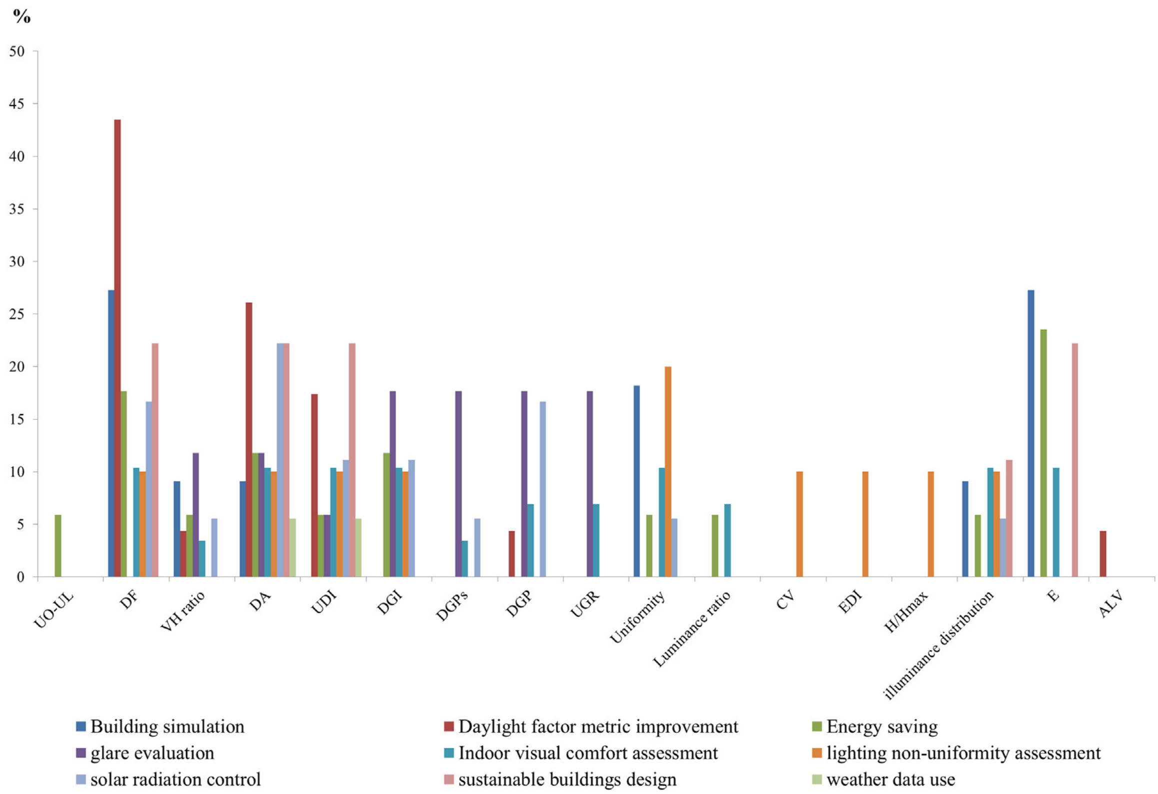

Fig. 1. Percentage of citations of each match index/area of interest with respect to the total number of citations.

illuminance values distribution and glare potential via a hybrid ray-tracing and radiosity method. The authors proposed four control strategies and two glare protections typologies based on the occupant's relative position. They studied different room sizes, glazing and blind material properties to validate the proposed model. They analysed DA, cDA, UDI and DGP variation. The authors observed that among the control strategies, the cut off angle control is still problematic, while light redirection control presents more promising results with lower transmittance glazing products. In the same way, Fasi and Budaiwi have studied the effects of automated venetian blinds in an office in a hot climate location. Additionally, in this case, energy saving and visual comfort have been considered, the latter evaluated by using DF and DGI. The authors have assessed how the installation of blinds increases the load of artificial lighting used to fulfil the inside lighting requirement and decrease the cooling energy demand [107].

A relation between visual and thermal comfort has been found by Wonuk et al. by using Artificial Neural Networks (ANN). The authors have used such a predictive model, which is able to correlate outdoor temperature and illuminance values, finding the correspondent energy saving percentage depends on these trends [108].

These studies highlighted how design strategies to ensure energy saving and proper visual conditions are strictly related to the assessment of natural lighting. Several indices can be utilized for these purposes although they present some peculiarities. With the aim of giving to the reader some hints about their adoption according to their scope, the following section provides an overview on the application of these indices in several areas of interest.

7. Discussion and conclusions

Several indices, able to assess natural lighting indoor conditions/availability, as well as visual comfort, have been critically analysed and reviewed. As highlighted in most cases, many indices are related to the same specific area of interest for their practical application. An analysis of bibliographic citations coming from academic papers, which refer to all the lighting indices presented in this paper, is then presented. Fig. 1 shows the percentage associated to each match between index and area of interest.

In particular, these areas are as follows: building simulation, lighting uniformity assessment, Daylight Factor improvement, daylight metrics improvement, glare evaluation, visual comfort, solar radiation control, sustainable building design, energy saving and weather data use.

As can be observed, DF is one of the most cited indices in the current literature. It can also be considered as a key-stone for developing other performance indices. Furthermore, it is mostly used for indoor visual comfort assessment, building simulation, energy saving and sustainable building design.

On the other hand, DA and UDI tend to overcompensate the shortcomings of DF and VH-ratio (which standardizes very different “lighting zones” even within the same space) to solve the issues related to the assessment of daylight during a time period. In addition, DA and UDI use actual weather data, adopt a visual acceptability threshold, support the improvement of other indices and allow the comparison among different weather data files and their impact on daylight simulations for artificial lighting design and consumption prediction. Nevertheless, these indices do not consider either the actual subject's comfort threshold or the spatial uniformity of luminance and illuminance.

Other indices must be cited for this latter purpose, i.e., the Uniformity Ratio, UO-UL, EDI, CV, and H/H_{max}. Today, most of these are not cited in standards for building design or visual comfort assessment and also require time consuming calculations. However, it is true that this particular field needs to be further investigated by the scientific community to ensure clear evaluation tools not only to guarantee proper indoor lighting analysis but also to support energy saving strategies in complex spaces.

UGR is exclusively utilized for assessing indoor comfort and in particular for glare assessment. It is a very useful tool to appreciate the indoor luminance distribution, although it cannot be utilized for assessing the distribution of illuminance.

DGI and DGP have a wide array of possible applications, although they are mostly utilized in glare assessment. In detail, the application of DGI is useful in building simulation and solar radiation control, and it can be adopted, for example, to evaluate the effect of shading devices in increasing artificial lighting use.

ALV provides more information about the indoor lighting quality, taking into account the "dynamic perceptual time" of the occupants.

Finally, it is possible to affirm that every index allows prediction and control, in different ways and levels of precision, of the main lighting and visual comfort parameters. The proper selection of daylighting indices can help researchers and designers characterize the daylight conditions in a building, assess how the occupant perceives and carries out a visual task and, where possible, reduce artificial lighting consumption.

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